Application of New Parameterizations for Atmospheric Boundary Layer and Oceanic Mixed Layer to Coupled Hurricane Modeling

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LONG-TERM GOAL

The long-term goal of this PI team is to understand the physical processes of the air-sea interaction and coupling of the atmosphere-ocean system in high-wind maritime regimes, with a particular emphasis on hurricanes, and to determine the changes that must be made to the coupled atmosphere-wave-ocean models in order to simulate the coupled boundary layers under extreme wind conditions. The ultimate goal is to produce a fully coupled atmosphere-wave-ocean model that can be used for high-resolution forecasts of hurricanes as well as for research.

OBJECTIVES

The main objectives of this study are 1) to develop improved subgrid-scale (SGS) parameterizations for modeling the atmosphere boundary layer (ABL) structure in high-wind regimes using a large-eddy simulation (LES) approach and explore the effects of sea spray on the ABL through LES experiments, 2) to test the sensitivity of mixing schemes in the ocean mixed layer (OML) and examine the effects of the ocean waves on the OML dynamics, and 3) to test various physical parameterizations in the fully coupled atmosphere-ocean models.

APPROACH

The extreme high winds, intense rainfall, large ocean surface waves, and copious sea spray push the surface-exchange parameters for temperature, water vapor and momentum to untested new regimes. We will develop improved parameterizations of subgrid-scale processes, air-sea exchange coefficients, and surface fluxes in coupled atmosphere-wave-ocean models with high-resolution (~1-2 km grid spacing) that can resolve the hurricane eyewall structure. The RSMAS/UM PI team is focusing on the effects of ocean wave "spectral tails" on drag coefficient, wind-wave coupling, and ocean mixed layer parameterizations. The PSU PI team develops improved parameterizations of subgrid-scale processes in ABL. The methodology is to use a Large-Eddy Simulation (LES) initialized for hurricane-like conditions, including very high winds, sea spray, and the effects of waves at the lower boundary. These parameterizations would then be installed and tested in the coupled atmosphere-wave-ocean models like the coupled modeling system at RSMAS/UM, the U. S. Navy's COAMPS, or the future coupled

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WRF system. We will work closely with the ONR supported CBLAST PI teams working on obtaining new observations of hurricanes to evaluate our model results.

WORK COMPLETED

During the first year of this project we have established several key steps toward developing a set of new coupling parameterizations for a fully coupled atmosphere-wave-ocean modeling system for hurricane research and prediction. First, in addition to the model simulation of Hurricane Floyd (1999), we have completed a 5-day wave model simulation of Hurricane Bonnie (1998) forced by the high-resolution surface winds from MM5. Using a vortex-following, four-level nested grids MM5, we are able to conduct a 5-day long simulation to capture the evolution and the landfall of Hurricane Bonnie at 1.67 km grid resolution on the inner-most domain (Rogers et al. 2003). The NECP global analysis fields and the high-resolution (~9 km) AVHRR Pathfinder analysis (Chen, et al., 2001) are used to initialize MM5 and provide continuous lateral and lower boundary conditions. Second, we have evaluated/validated model simulated surface wave spectra with observations both over the open ocean and at the landfall (Walsh et al. 2001). Third, we have added new vertical mixing submodels to HYCOM, and has validated the performance of the model and the hybrid vertical coordinate adjustment algorithm using all available vertical mixing algorithms.

The Penn State group held a 2-day workshop on sea spray in hurricanes during August, with both Ed Andreas and Chris Fairall participating. Two people are working on putting their parameterizations into MM5. Thus far we have implemented Fairall's parameterization into your version of MM5 and are in the process of testing it. Topics discussed at the workshop focused predominantly on the physical and thermodynamic representation of spray/spume generation, including implementation of spray and spume physics into three-dimensional LES. The workshop addressed the limitations of the one-dimensional Andreas and Fairall spray parameterizations, leading to discussion of representation of spray in three dimensions. Resolution-related issues near the simulated ocean boundary were also discussed, including how LES can improve upon previous 1-D work, as well as talking about the need for parameterization of subgrid fluxes of spray, water vapor, and sensible heat. The workshop explored further the implementation of spray generation in two dimensions and its thermodynamic consequences, in relation to the previous works of Fairall and Andreas. The meeting solidified (revision of) plans for the ongoing LES implementation.

The initial LES implementation includes spray generation and associated sensible heat flux (due to corresponding fallout) at a single vertical level while varying quasi-randomly in the horizontal plane. This is done using Andreas' spray generation function and is based on both laboratory and ocean measurements of breaking waves and spray/spume generation. A radius-dependent eddy diffusivity is used in the turbulent transport of spray, and the effects of slip and liquid loading are included in the dynamic LES equations. Due to the large liquid water mixing ratios near the surface, the exact (nonlinear) thermodynamic effects are also included in the thermodynamic equations. An initial investigation will test the utility of several conserved temperature variables to resolve this issue.

RESULTS

We have conducted a number of coupled MM5-WW3 simulations to investigate the sensitivity of model simulated hurricane intensity to various wind-wave coupling parameterizations. Fig. 1 shows the simulated minimum sea level pressure (SLP) for Hurricane Floyd (1999) using three different wind-wave couplings 1) roughness length from a simple friction velocity relationship, 2) wave-age dependent roughness length, and 3) directional stress coupling with our spectral-tail parameterization. The storm intensity varies by 15-20 m s^{-1} with different wind-wave couplings. The directional stress coupling seems to be the closest one to that observed from the best track record.

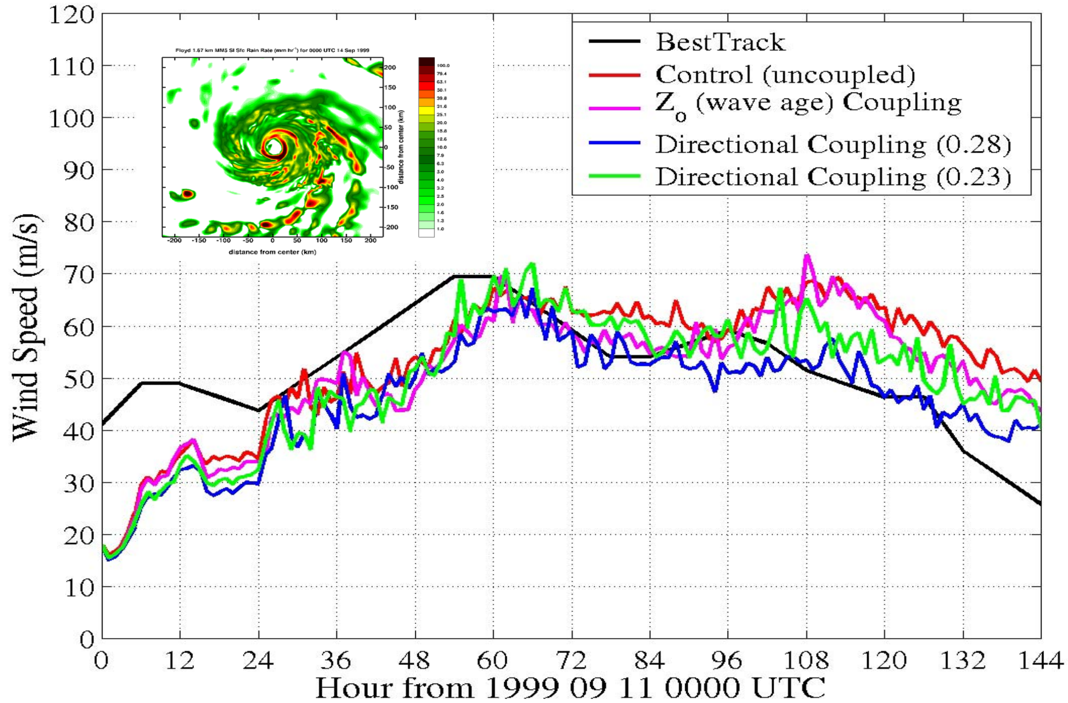

Fig. 1 Coupled MM5-WW3 simulations of storm intensity for Hurricane Floyd (1999) using three different wind-wave coupling parameterizations.

resolution, inadequate surface and boundary layer formulations, and lack of full coupling to the ocean. This project will provide improved physical parameterizations for the coupled atmosphere-wave-ocean models at very high spatial resolution. It will make a significant contribution to improve hurricane intensity predictions.

The PSU PIs are using Otte's version of Moeng's LES code to simulates a 3D, horizontally periodic piece (nominally a few km in the horizontal and a few km deep) of the atmospheric boundary layer. Modifying the code for the moist, hurricane boundary layer requires five steps: (1) including liquid water, phase change, and a conserved moist thermodynamic variable; (2) including subgrid-scale condensation effects; (3) determining the required resolution for boundary layer transport processes and the performance of subgrid-scale models; (4) allowing for the injection of sea spray; and (5) dynamic coupling to the wavy sea surface.

The first three steps have been completed. We use a 12.5 m x 12.5 m x 13.9 m numerical grid and a stochastic subgrid condensation model. Figures 2 and 3 show results of a simulation with 50 m/s winds and a spray injection rate of 5 g/kg m/s (suggested by Chris Fairall, personal communication). The vertical velocity field just before the spray injection is shown in Fig. 2, and that field 1000 s later is shown in Fig. 3. This simulation was performed with non-evaporating spray to highlight the stabilization caused solely by the mass-loading effects of the spray. Figure 4 shows time series of the surface-exchange coefficient of enthalpy for a series of similar runs but with different wind speeds and spray injection rates. All simulations show reductions in the exchange coefficient.

We are now working on step (4) and have performed initial LES tests of the behavior of the hurricane boundary layer for various rates of spray injection. We are continuing to implement more realistic spray physics in our LES code, collaborating with Ed Andreas. Our LES will allow for spray injection at more than one level, consistent with the emulsion-like nature of the sea-air interface under hurricanes recently noted by Emanuel (2003). We are adapting a representation of grid-averaged spray content over different droplet size ranges, with spray evaporation (and condensation). The spray 'species' representing several droplet size ranges interact through known microphysics and are generated using a model based on Andreas (1998). The spray scalar species have fall speeds and lose heat to the atmosphere based on their representative radii (r_n), where the effective droplet temperatures and heat transfer rates are also based on microphysics. The subgrid-scale and subsaturated phase-change scheme varies with the spray droplet radius and follows from our previous work.

The surface (non-wavy at present) representation in our LES allows realistic horizontal variation of the spray generation and injection rate, with a stochastic component as well as a component dependent on the local wind velocity. The surface roughness is dependent on the friction velocity and also varies along the 'surface.' Thus, the local surface fluxes vary in the *x-y* plane and in time. We shall diagnose the surface-exchange coefficients for various averaging areas and resolutions based on horizontal plane averages of surface fluxes and the relevant flow variables (e.g., temperature, momentum). We have already done this for simple inert spray simulations, as noted above. We shall evaluate the variability in bulk surface-exchange coefficients and eddy diffusivities, and examine the physical feedbacks leading to these variabilities as well as the general trends in the coefficients. We have also begun work on step (5), including the dynamic coupling to the sea surface through modulation of the vertical velocity at the surface. We plan to inject sea spray dynamically as well, using Andreas' models of spray production and Melville's statistics of wave breaking.

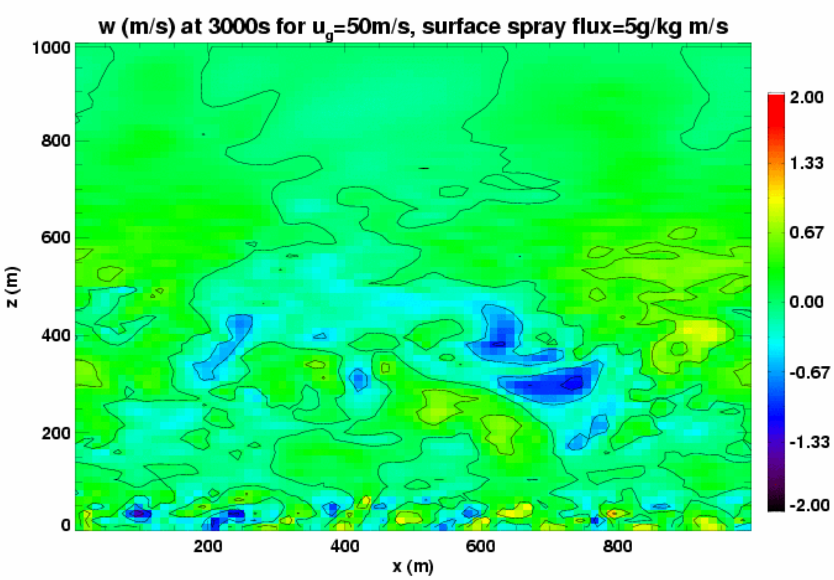

Fig. 2

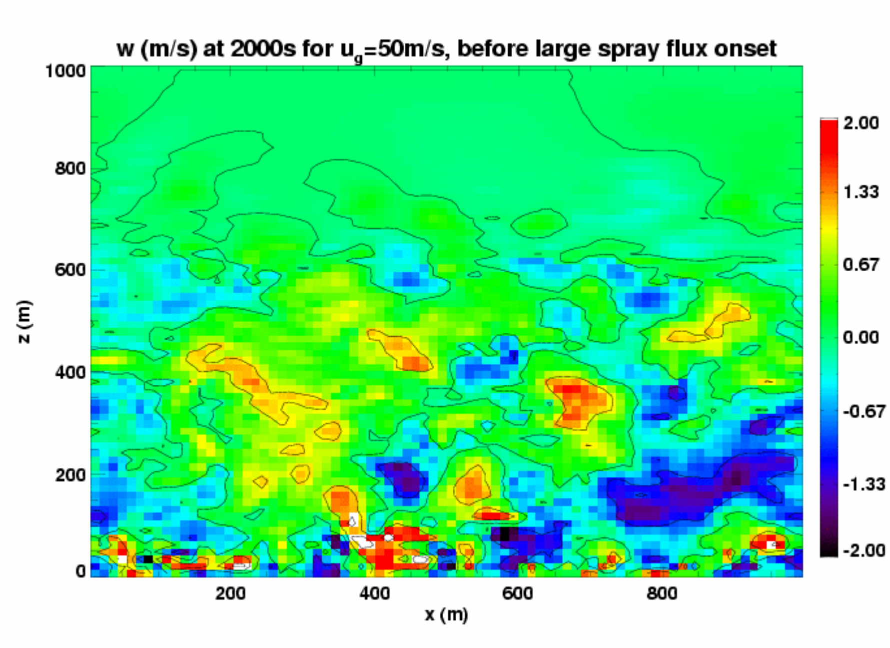

Fig. 3

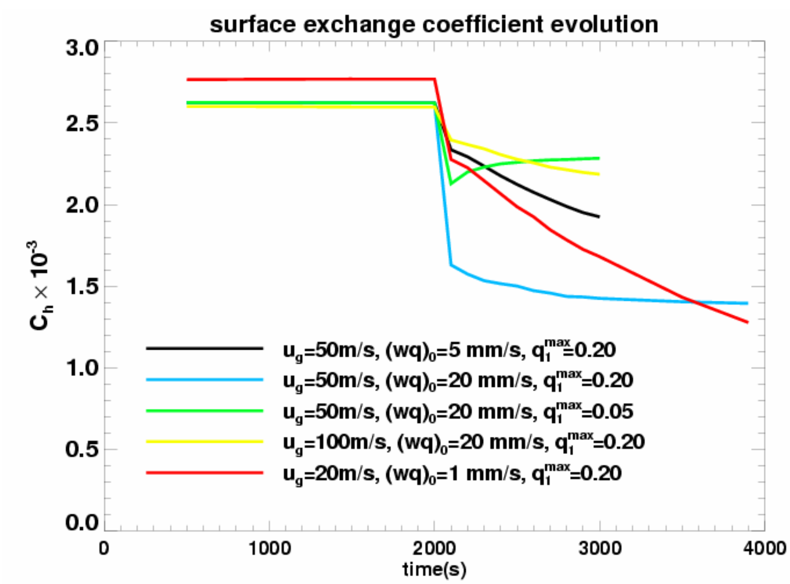

Fig. 4

We have already demonstrated significant dynamical effects of sea spray upon surface fluxes and the near-surface stability. Such effects are but one example of a dynamical feedback due to spray; we shall examine others. Unlike other approaches, high-resolution LES allows their explicit calculation in the hurricane boundary layer. LES also permits inspection of local physical phenomena on varying spatial and temporal scales and provides a broad array of statistical measures of the flow. Our scheme permits 2-way thermodynamic and mechanical feedback between the spray and flow, as well as 2-way phase changes. The LES represents spray and spray-mediated fluxes explicitly and three-dimensionally, in strong contrast to parameterized 1-d models. Our LES approach allows examination of the effects of spatially varying surface fluxes and roughness, as well as both local and average effects of spray.

Finally, we can inspect the dependences of bulk quantities (such as the ratio of enthalpy to momentum surface exchange coefficients), calculate their variability, and explore mechanisms responsible for their variations.

IMPACT/APPLICATIONS

Over the last a few decades hurricane track forecasts have improved significantly, whereas very little progress made in hurricane intensity forecasts. The lack of the skill in the intensity forecasts can be attributed, in part, to deficiencies in the current operational prediction models: insufficient model resolution, inadequate surface and boundary layer formulations, and lack of full coupling to the ocean. This project will provide improved physical parameterizations for the coupled atmosphere-wave-ocean models at very high spatial resolution. It will make a significant contribution to improve hurricane intensity predictions.

TRANSITIONS

We will assist in the transitioning of the completed parameterizations to operational coupled modeling systems (e.g., COAMPS). These new parameterizations developed at RSMAS/U.Miami and Penn State will be made available for all ONR CBLAST PIs.

RELATED PROJECTS

Related projects include the NSF/NOAA/ONR USWRP on Rainfall of Hurricanes at Landfall (S. Chen), the NASA/JPL QuikSCAT (S. Chen), ONR HYCOM Consortium for Data Assimilative Ocean Modeling (E. Chassignet, G. Halliwell, et al.), and ONR CBLAST-Hurricane (P. Black et al.).

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